ELECTROSTRICTION OF POLYMER FILMS FOR MICROACTUATORS

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ABSTRACT

The investigation of electrostrictive polymers (EPs) as a means of microactuation is described. EP materials are squeezed and stretched by electrostatic forces generated with compliant electrodes. This approach offers several advantages over existing actuator technologies, including high strains (> 30%), good actuation pressures (1.9 MPa), and high specific energy densities (0.1 J/g). In addition, the actuation is fast, uses lightweight materials, and has the potential for high energy efficiencies. Although EP actuators are electrostatics based, they offer 5 to 20 times the effective actuation pressure of conventional air-gap electrostatics at the same electric field strength. The gain is due to replacing air with a higher dielectric material, and to using two orthogonal modes of electromechanical coupling (stretching and squeezing) rather than one. Analysis of the mechanism of EP actuation is discussed. We also discuss fabrication techniques such as spin coating, casting, and dipping, as well as polymer and electrode materials. We describe demonstrations of prototype mini- and microactuators in a variety of configurations such as stretched films, stacks, rolls, tubes, and unimorphs. Last, we suggest potential applications of the technology in areas such as microrobots, sound generators, and displays.

INTRODUCTION

Many types of microactuator technologies have been demonstrated or proposed for microdevices, including electrostatic, electromagnetic, and piezoelectric [1,2,3,4]. Existing technologies have limitations in one or more performance parameters, such as strain, actuation pressure, speed of response, and efficiency. For example, electrostatic actuators generally have low actuation pressures and high operating voltages; electromagnetic microactuators have low efficiency; shape memory alloy has slow speed of response; and piezoelectric microactuators have limited strain.

These limitations are not important for some applications, but for applications such as mobile microrobots, which require good performance in all categories, these limitations are significant. There is, therefore, a need for a general-purpose microactuator technology with good overall performance. Such a technology could play the role on microscales that electromagnetic technology plays on macroscales.

The electrostrictive polymers (EPs) we describe are promising as a general-purpose microactuator technology with good performance. These polymers are often described as *artificial muscle* because their performance is comparable to that of natural muscle and, like that of natural muscle, is scale invariant.

PRINCIPLE OF OPERATION

Many types of electrostrictive polymers exist. The actuation mechanism for some EP materials involves molecular changes [5], while for others the actuation mechanism can best be described in terms of bulk electrical and mechanical properties [6]. We have focused on the latter materials, where the critical properties are the relative dielectric constant, ε; breakdown strength; and modulus of elasticity, Y.

Figure I illustrates the principle of operation of EP actuators. An elastomeric polymer film is sandwiched between two compliant electrodes. When a voltage difference is applied between the electrodes, the polymer is squeezed in thickness and stretched in length and width.

The basic unit shown in Figure I can be used in various ways to make a microactuator. A single layer of film with active and inactive regions can be stretched on a rigid frame to make a stretched film actuator. Figure II shows photographs of such a film with the voltage on and off. More complex configurations, such as multilayer stacks, rolls, tubes, and unimorphs, have also been demonstrated and are discussed later.

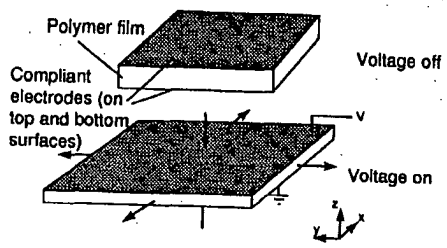

Figure I. Principle of operation of an electrostrictive polymer actuator

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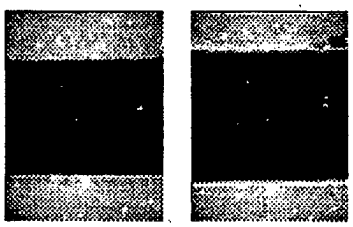
Although the principle of operation shown in Figure I is conceptually simple, several subtle features affect the performance and fabrication of the device.



Voltage Off Voltage On

Views from above of a 50-μm-thick silicone rubber film with 1-mm wide, vapor-deposited carbon electrodes expanding when a voltage is applied to the electrodes

Figure II. Photographs showing expansion of polymer (top view; black areas are 1-mm-wide electrodes)

One significant difference, in comparison to conventional electrostatic actuators, is that the relative dielectric constant of the polymer is typically 2.5 to 10 or more. This contrasts with conventional electrostatic actuators, which operate with air gaps having dielectric constants very nearly 1.0. The difference in dielectric constant means that EP actuators have much greater actuation pressure than conventional electrostatic actuators at a given electric field strength. The *effective actuation pressure*, p, of the EP material shown in Figure I is given by [7,8]:

$$p = \varepsilon \varepsilon_0 E^2 \qquad (1)$$

where ε_0 is the permittivity of free space (8.85×10^{-12} F/m) and E is the electric field in V/m.

A second difference to note from Figure I is that the compliant electrodes stretch as well as move closer together (the polymer compresses). The two modes, stretching and compressing, are mechanically coupled by the volume incompressibility of the polymer (i.e., polymer volume is conserved during actuation; mathematically, this occurs because the Poisson ratio of many elastomers is essentially 0.5).

The two modes, stretching and compressing, double the effective actuation pressure, whereas rigid electrodes can only compress closer together. This difference is reflected in Equation (1) by the absence of the usual factor of 0.5 with rigid-electrode electrostatic actuators.

Taken together, the effects of the dielectric constant and the two modes of actuation typically increase the effective actuation pressure by a factor of 5 to 20, at a given field strength, over that of conventional electrostatic actuators.

The strain of EP materials can be large, exceeding 30% strain in thickness. Below roughly 5% strain in thickness, the strain for an unconstrained EP film (free boundary conditions) can be approximated by

$$s_z = -p/Y = -\varepsilon \varepsilon_0 E^2/Y = -\varepsilon \varepsilon_0 V^2/(2Yt_o) \qquad (2)$$

where s_z is the thickness strain, V is the applied voltage, and t_o is the initial (nonactuated) polymer thickness. Here, we are assuming that compliant electrodes do not add any stiffness to the structure. If they do, they can be included as an effective modulus of elasticity, Y.

The strains in the plane of the film can be calculated from Equation (2) together with the volume incompressibility constraint:

$$(1+s_x)(1+s_y)(1+s_z) = 1 \qquad (3)$$

where s_x and s_y are the in-plane strains. For a film that is isotropic in the in-plane directions, it is easy to show from Equation (3) that for small strains

$$s_x = s_y = -0.5\, s_z \qquad (4)$$

Equation (2) is still valid for large strains, provided the actuated thickness, t_a, is substituted for the initial polymer thickness, t_o. However, the actuated thickness depends on the strain itself, and for large strains this effect is not negligible.

PERFORMANCE OF ELECTROSTRICTIVE POLYMERS

Table I shows the performance of electrostrictive polymers. Various polymers have demonstrated a strain of greater than 10%. As can be seen from the table, silicone polymers (e.g., Dow Corning Sylgard*) have given the highest strain performance (32%), while polyurethane has demonstrated the highest actuation pressures (1.9 MPa) (e.g., Deerfield PT6100s).

Table I. Measured Performance of Various Polymer Dielectrics

Polymer	Energy Density J/cm^3	Strain %	Pressure MPa	Young's Modulus MPa
Polyurethane	0.10	11	1.9	17
Silicone	0.034	32	0.21	0.7
Fluorosilicone	0.019	28	0.14	0.5
Ethylene propylene	0.0072	12	0.12	0.3-2.1
Polybutadiene	0.011	12	0.19	1.7
Isoprene	0.0052	11	0.094	0.85

*All product names mentioned in this paper are the trademarks of their respective holders.

The in-plane strains s_x and s_y were measured directly with the reticle of an optical microscope, and the thickness strain in Table I was calculated by using Equation (3). Actuation pressure was based on the measured modulus together with the measured strain.

The pressure response time of EP materials has been measured at less than 4 ms by using a load cell; however, this measurement was limited by the response of the load cell and the driving electronics. Since the films can be heard at much higher acoustic frequencies, up to 10 kHz, it seems likely that the actual response time is below 1 ms. Fundamentally, the response time appears to be limited only by the speed of sound in the material and by the rate at which charge can be placed on the electrodes.

Energy efficiency, an important parameter for some applications, is estimated at 80 to 90% at actuation rates of 1 to 20 Hz. This estimate is based on calculation of the electrical leakage current together with stress-strain measurements of mechanical hysteresis. At higher rates of actuation, the leakage loss per cycle is reduced, thus increasing efficiency. However, hysteresis losses have not been measured at higher frequencies.

The estimated efficiency assumes charge recovery. Even without charge recovery, relatively good efficiency (10 to 50%) should be feasible, based on the large strains observed, because as the strain increases, the opposite charges draws closer and the like charges spread out. Hence, more electrical energy is converted to mechanical work.

Figure III is a graph comparing the measured performance of electrostrictive polymers with other high-speed actuation technologies. The horizontal axis is the effective actuation pressure divided by the material density, an important parameter for weight-limited mobile applications such as mobile microrobots. Note that while existing high-speed technologies have good performance in either strain or actuation pressure/density, electrostrictive polymers have good performance in both parameters. Note also that EP performance is comparable to that of natural muscle.

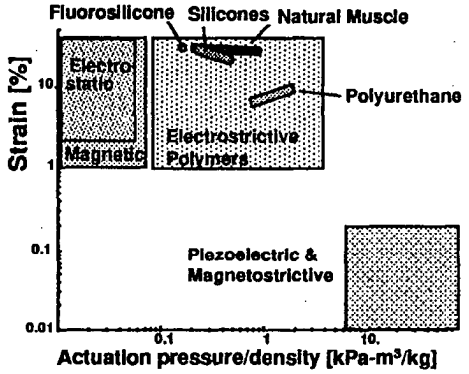


Figure III. Comparison of high-speed actuator technologies

FABRICATION

Electrostrictive polymer actuators can be fabricated by a number of techniques. Most processes start with dispersing an uncured polymer in a solvent or liquid carrier to reduce viscosity. Ideally, the polymer is also purified. We have observed, for example, that centrifuging commercial polymers can significantly increase performance. One fluorosilicone (Dow Corning RTV730) increased its maximum actuated strain from 14% to 28% as a result of centrifuging.

For a given polymer, the allowable operating voltage determines the desired film thickness. Unlike air gap actuators, there is no Paschen effect with the polymers, so there is no intrinsic need for submicron thicknesses. Further, the polymer thickness itself controls the electrode spacing, which eliminates the need for complicated spring or bearing arrangements to maintain spacing.

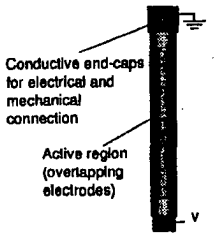
The electric breakdown strength of elastomer films (e.g., silicones, polyurethanes, fluorosilicones) is typically in the range of 50 to 200 MV/m, although some films can have higher strengths. This breakdown strength is significantly higher than that of bulk materials, probably because of the reduced likelihood of defects.

Typically, the films are operated below breakdown strength to maintain a margin of safety. Thus, if an operating voltage of 200 V is desired, film thickness should be in the range of 1 to a few μm for optimal performance. Spin coating techniques, similar to those used to spin photoresist on silicon wafers, can be used to make films of this thickness. We have used spin coating to fabricate and release silicone films down to a thickness of 1 μm.

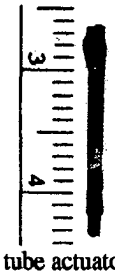
If higher operating voltages are allowed, thicker films can be used. Thicker films can also be used if the dielectric constant is high because lower electric field strengths are needed for the same mechanical output, as indicated in Equations (1) and (2). For thicker films, other techniques such as casting and dip coating are applicable. These techniques are attractive because they can be used to make complex shapes. Figure IV, for example, shows a tube actuator made by dip coating.

Compliant electrodes must also be fabricated on the polymer film. Various electrode materials have been demonstrated, including graphite powder, ultra-thin gold (100 to 200 Å), carbon fibrils, and conductive rubber. The ideal electrode would be perfectly compliant and patternable, and could be made thin relative to the polymer thickness. For thicker films, powder-based electrodes with elastomeric binders work well and can be spray coated in patterns.

For thinner films, electrode fabrication is more difficult and is an area of active research. We have demonstrated conductive rubber films down to a thickness of 0.25 μm.



(a) Schematic of the actuator structure



(b) Photograph of a tube actuator (1 division = 1 mm)

Figure IV. Tube actuator made by dip coating

These films can be patterned by using selective wetting of water-based latex solutions. With this technique, we have fabricated eight-layer (four layers of polymer and four layers of electrodes) electrostrictive polymer actuators by depositing each layer directly on top of the previously deposited one.

Driver electronics can play a key role in determining fabrication requirements. In many instances, conventional high-voltage components can be used to drive several microactuators remotely. With high voltages, the electric power can be efficiently transmitted through thin conductive traces. In some cases, however, it may be desirable to miniaturize the driving electronics as well. For this reason, we are investigating ways to amplify voltage by using small voltage multiplier circuits or microtransformers. Simple voltage multiplier circuits appear promising for miniaturization. For example, a 4X voltage multiplier uses only four diodes and four capacitors, all of which can be microfabricated. The voltage amplification can be separate from the actuator, or it can be packaged with the electrostrictive polymer to make an integrated actuator. The latter approach is attractive, because to external circuits the actuator would then appear as a low-voltage device.

PROTOTYPE ACTUATORS

Various prototype or proof-of-principle actuators with electrostrictive polymers have been used to demonstrate the flexibility of the technology, to refine the fabrication techniques, to identify potential problems, and for long-term reliability testing. Most of the work to date has focused on relatively simple structures on the millimeter size scale. With patterned electrodes, however, EP technology has potential for complex actuators such as arrays and multiple-phase or multiple-degree-of-freedom devices of microscopic sizes. Work has begun in these areas.

The simplest actuators are stretched film such as the one shown in Figure II. Both single- and multiple-layer films can be used. Stretched film actuators have achieved the lowest operating voltages (approximately 20% strain at 300 V and significant strain at 200 V and lower). The stretched film can function by itself (e.g., as a light modulator), or an output shaft can be attached to the film to make a linear actuator. An example of such a linear actuator is shown in Figure V. Arrays of stretched film actuators are relatively easy to pattern, and 3 × 3 arrays have been successfully demonstrated. Stretched film actuators with active areas as small as 200 μm have been fabricated, as have two phase actuators. Because they are fabricated by techniques similar to those that are well known for microelectronics, stretched film actuators offer the best short-term approach to submillimeter microactuator fabrication for MEMS applications.

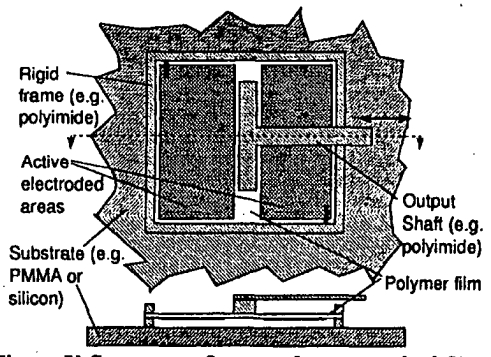
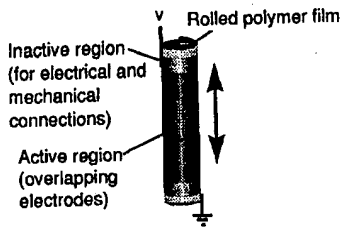
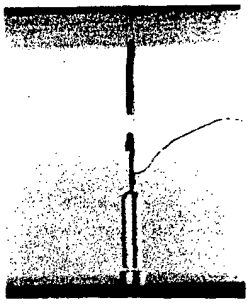


Figure V. Structure of a two-phase stretched film microactuator

Rolled actuators have been built with more than 20 layers measured through the diameter. Figure VI is a photograph of a rolled actuator. Rolled actuators can be built by starting with a single layer of film and then folding and rolling on pins. Alternatively, a double-layer film can be made by *in situ* fabrication or by stacking, and then rolling. Connections are typically made by pushing a sharp wire directly through each end of the roll. Rolling a thin, 25-μm wire with the polymer also works well. Dimensions are typically 5 to 20 mm in length and 1 to 5 mm in diameter. Peak displacements up to 10% of the length have been measured. Forces are typically 1 to 10 g, although rolled actuators to date have used lower-force EP materials. Much higher forces should soon be feasible. Rolled actuators have been demonstrated at over 1 million cycles with minimal performance degradation.



(a) Schematic of the actuator structure

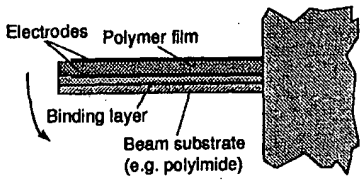


(b) Photograph of a rolled actuator lifting a 1-g weight

Figure VI. Rolled actuator

Tube actuators such as the one shown in Figure IV have been made by dipping in sizes from 1 to 10 mm. Tubes have been demonstrated at forces up to 30 g with strains of 5 to 10%.

Unimorph actuators, as shown in Figure VII, have also been demonstrated on the millimeter scale. This type of actuator is well known from the piezoelectric field. Angular deflections of 90 degrees have been demonstrated. Relative to piezoelectric unimorphs and bimorphs, electrostrictive polymer unimorphs should be capable of smaller radii of curvature, owing to their much greater strain. Like a stretched film actuator, a unimorph can easily be made on a microscopic scale by patterning with photolithographic and liftoff methods.



(a) Schematic of the actuator structure

(b) Photograph of a unimorph actuator

Figure VII. Unimorph actuator

APPLICATIONS OF EP ACTUATORS

Electrostrictive polymers have good overall performance and are scale invariant. They can also be configured in various ways and shapes. These factors make them potentially applicable to a wide range of micro- and minidevices. However, as indicated in Figure III, the performance capabilities of EP actuators are not available with existing technologies, so an active area of research is that of identifying optimal actuator designs that best exploit EP capabilities.

The potential applications discussed here are not meant as a complete list. Rather, they are intended to stimulate the thinking of the MEMS community on how EP actuators might be exploited in future devices.

As we have mentioned, mobile microrobots are a good application for EP actuators. On micro- or minirobots, EP actuators could be used in grippers, legs, inchworm-like drives, and sensor-scanning devices. Mobile applications in general are a good match of requirements with EP performance (i.e., light in weight, good to excellent in efficiency, with high strain and force).

High-speed devices are attractive applications for EP actuators. Sound generation is an example of a high-speed application, and, as noted earlier, we have already observed sound generation from our actuators driven at high frequencies. This application is particularly attractive because EP materials have the large strains needed for low-frequency sound generation. In contrast, piezoelectric approaches do well at high frequencies but are limited by their small strains at low frequencies.

Micropumps and microvalves are another application area for EP actuators. Here, both high speed and large strains are important to achieving high flow rates. An example in this area is the inkjet printers. The actuation pressure of various EP materials covers the range of pressures used in current piezoelectric or bubble jet printers. Another area that could benefit from a compact, high-performance micropump or microvalve is on-chip biological or chemical analysis.

Displays and other optical devices may benefit from EP capabilities. We have noted that simple EP actuator arrays have already been demonstrated, and the relatively large displacements that are possible suggest display applications. In this respect it is also encouraging that the materials themselves are very low in cost and rugged, so large-area displays are an option (unlike silicon-based displays, which are prohibitively expensive and relatively fragile in large areas). We have demonstrated stretched film actuators as large as 0.1 m, and there is no apparent reason why they could not be made much larger.

Electrostrictive polymers also could be used as "smart materials" that sense as well as actuate. When an EP actuator is stretched, from actuation or from external forces, the capacitance, as measured across the electrodes, changes. Thus, one could imagine applications such as smart skins that could undergo and sense large displacements, yet could also be actuated for gripping and other functions.

CONCLUSION

Electrostrictive polymers have been demonstrated with overall performance comparable to that of natural muscle. Unlike existing microactuator technologies, which are generally deficient in one or more measures of performance, electrostrictive polymer technology results in good performance in all categories, including strain, actuation pressure, efficiency, speed of response, and density. Performance is scale invariant, and proof-of-principle actuators have been in made with active areas ranging in size from 200 μm to 0.1 m. Fabrication techniques have been developed to make a variety of EP configurations, including micrometer-thick films, tubes, rolls, stacks, and unimorphs.

The generally good performance of EP actuators makes them potentially applicable for a wide range of devices such as microrobot actuators, sound generators, displays, inkjets, and smart skins.

Future R&D is focused on identifying materials with still higher performance; fabrication (particularly *in situ* fabrication of microscopic devices and multilayer, thin-film stacks); and improved electronic drivers such as integrated microvoltage amplifiers, as well as on generating and demonstrating actuator designs that best exploit electrostrictive polymer capabilities.

ACKNOWLEDGMENTS

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